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On the formation of single and binary helium-rich sdO stars

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ABSTRACT
We propose a formation channel for the previously unexplained helium-rich subdwarf O (He-rich sdO) stars in which post-subdwarf B (sdB) stars (i.e. hybrid COHe white dwarfs) reignite helium burning in a shell after gaining matter from their helium white-dwarf (WD) companions. Such short-period binaries containing post-sdB WDs and helium WDs are predicted by one of the major binary formation channels for sdB stars. In the majority of cases, mass transfer is expected to lead to a dynamically unstable merger event, leaving a single-star remnant. Calculations of the evolution of these stars show that their properties are consistent with the observed He-rich sdO stars. The luminosity of these stars is about an order of magnitude higher than that of canonical sdB stars. We also suggest that binary systems such as PG 1544+488 (Ahmad et al. 2004) and HE 0301-3039 (Lisker et al. 2004), which each contain two hot subdwarfs, could be the outcome of a double-core common-envelope phase. Since this favours intermediate-mass progenitors, this may also explain why the subdwarfs in these systems are He-rich.

Key words: binaries: close – subdwarfs – white dwarfs.

1 INTRODUCTION

In recent years there has been an extensive debate over the origin of hot subdwarf stars, largely because they seem to provide the best explanation for the UV-upturn seen in elliptical galaxies (e.g. Yi, Demarque & Oemler 1997, 1998; Han, Podsiadlowski & Lynas-Gray 2007). The production of such stars in globular clusters, where they are often referred to as *extreme horizontal branch* (EHB) stars, has been a long-standing mystery (see, e.g., van den Bergh 1967; Sandage & Wildey 1967; Soker 1998; Han 2008).

Subdwarf B (sdB) stars are believed to be helium-core-burning stars with masses ~ 0.5 $M_\odot$, posessing very small (< 0.02 $M_\odot$) hydrogen-rich envelopes (Heber 1986; Saffer et al. 1994). Their formation has been studied in some detail by Han et al. (2002 & 2003), who showed that binary evolution can account for the properties of the observed sdB stars. Other authors have suggested enhanced mass-loss from single red-giant stars in order to try to explain the formation of sdB stars (e.g. Yi et al. 1997; see also Han, Podsiadlowski & Eggleton 1994), or mixing driven by a very late helium flash (Sweigart 1997; Brown et al. 2001), or that interactions with planets can eject the envelopes of red giants (Soker 1998; Nelemans & Tauris 1998).

Subdwarf O (sdO) stars are assumed to be related to sdB stars. Stroeer et al. (2007) have examined the formation of sdO stars and concluded that the sdO stars with a subsolar photospheric helium abundance ('helium-deficient') have a different origin to the 'helium-enriched' (He-rich) sdO stars (which they define as having a super-solar helium abundance). Specifically, Stroeer et al. found that the helium-deficient sdO stars are likely to be evolved sdB stars, but that the He-rich sdO stars cannot be explained through the canonical evolution of sdB stars.[1] Proposed formation channels for those He-rich sdO stars include mergers of two helium white dwarfs (Saio & Jeffery 2000) and the 'hot flasher scenario' (e.g. Moehler et al. 2007; Miller Bertolami et al. 2008). Though neither of these models seems entirely satisfactory, one piece of evidence which apparently favours the white-dwarf merger scenario is the very low binary fraction of the He-rich sdO stars (see, e.g., Heber et al. 2006; Heber 2008). Here we show that the existence of He-rich sdO stars,

[1] Zhang, Chen & Han (2009) have also tried to constrain the fraction of sdO stars which can simply be evolved sdB stars and which fraction requires another explanation.

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including single ones, is a natural consequence of one of the binary formation channels for sdB stars.[2]

Section 2 explains the proposed formation channel, where section 2.1 presents evolutionary calculations and section 2.2 compares population synthesis expectations to the observed sample of He-rich sdO stars. Section 3 then introduces a new formation channel for double hot subdwarfs and examines its possible implications.

2 A NEW MERGER CHANNEL

The merger of a helium white dwarf (WD) with a post-sdB star is predicted in one of the important binary channels for the formation of sdB stars (Han et al. 2002; 2003), but has not been considered in detail before. Here we propose that such mergers are the natural progenitors of He-rich sdO stars.

Han et al. (2002 & 2003) showed that a significant fraction of sdB stars is expected to exist in short-period binaries containing a helium WD (see Fig. 1). This is the result of the 'second common-envelope channel', where a WD spirals into the giant envelope of the sdB progenitor, thereby ejecting that envelope. After the helium-burning phase of the sdB star has been completed, the remnant will become a hybrid WD with a carbon-oxygen (CO) core and a thick helium (He) envelope. If the orbital period is short enough,[3] gravitational radiation will drive the binary components towards each other until eventually mass transfer is initiated from the lighter helium WD onto the post-sdB He-CO WD star. Once a sufficiently thick helium shell has been built up around the CO core, helium will (re-)ignite in this shell. In the following section, we will show that such objects have all the main observational characteristics of He-rich sdO stars.

Following the pioneering work of Saio & Nomoto (1998), Saio & Jeffery (2000, 2002) simulated the merger of white dwarfs (first of two He WDs and later of a 0.6 $M_\odot$ CO WD accreting from a He WD). The situation we consider here is very similar; even though our calculations in section 2.1 do not treat the mass-transfer/merger phase, the work of Saio & Jeffery strongly suggests that the post-merger star will undergo stable helium burning, with weak He shell flashes during the accretion phase. We cannot completely exclude the possibility of catastrophic explosive He burning that could destroy the star or eject a large fraction of the accreted envelope, but the accretion rates in this case are significantly higher than those predicted to produce '.Ia' supernovae (see, e.g., Bildsten et al. 2007; Shen & Bildsten 2009). However, since we cannot properly calculate the burning during the accretion phase, we cannot show how the newly-reignited systems behave during their approach to equilibrium.[4] In principle, some of the observed He-sdOs could be systems which have not yet attained their thermal equilibrium structure.

[2] Our proposed formation channel seems unable to produce the class of He-rich sdB stars (Naslim et al. (2010); we discuss the implications of this in section 2.4.

[3] Typically $\lesssim 7$ hr for interaction within a Hubble time; see footnote 8.

[4] Note that the details of the ignition phase should depend on the accretion rate (see, e.g., Saio & Nomoto 1998).

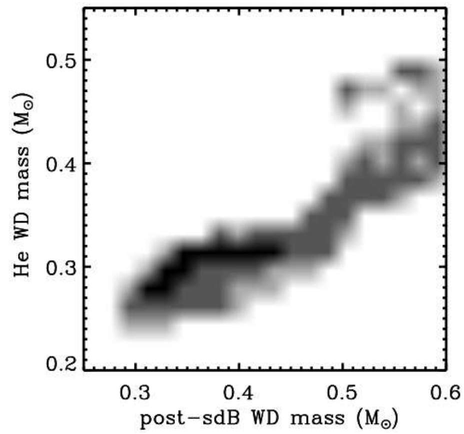

Figure 1. The pre-merger distribution of the component masses of binary systems expected to produce He-rich sdO stars (taken from the preferred binary population synthesis model of Han et al. [2003]). Darker colours indicate more systems. Once the mass of the sdB star approaches 0.6 $M_\odot$, the outcome of the mass-transfer episode is better described by the CO+He WD merger calculations of Saio & Jeffery (2002). The stellar evolution calculations in this paper use representative post-sdB masses of 0.35, 0.4 and 0.46 $M_\odot$.

Not all of these systems should experience dynamically unstable mass transfer. The results of Han & Webbink (1999) indicate that the mass transfer from the helium white dwarf in these systems will usually be dynamically unstable, leading to a merger and ultimately a single He-rich sdO star. This may naturally explain the high fraction of apparently single He-rich sdO stars (see, e.g., Stroeer et al. 2007). However, the systems which undergo a stable mass-transfer phase could potentially leave binary He-rich sdO stars. In this case, the sdO star could still be in a close binary with an orbital period $\lesssim 2$ hr and be accreting at a low rate from a potentially very low-mass companion (i.e. a few 0.01 $M_\odot$; see, e.g., Fig. 7 in Rappaport, Podsiadlowski & Horev [2009]; also see the case of the millisecond pulsar PSR 1957+20 [Fruchter et al. 1988]).

2.1 Post-merger calculations

For our stellar evolution calculations we used Eggleton's stellar evolution code (Eggleton 1971; Pols et al. 1995) with a metallicity of 0.02 along with the convective overshooting calibration of Pols et al. (1998). We first evolved a set of sdB stars using sdB models from Han et al. (2002, 2003) in order to produce a set of post-sdB models onto which matter was added from an assumed helium WD companion.

For the sdB stars which undergo shell burning, we generally found it necessary to perform the merger very late in the growth of the sdB core, but before the helium burning had completely finished. This avoids having to ignite helium degenerately, though we still regularly found steep and numerically troublesome increases in the nuclear energy generation rate as we added the matter from the He WD. During the merger process, we artificially switched off the nuclear evolution of the object (the energy generation continued as normal but the composition was frozen). To some extent, this enabled us to add the mass as slowly as was required

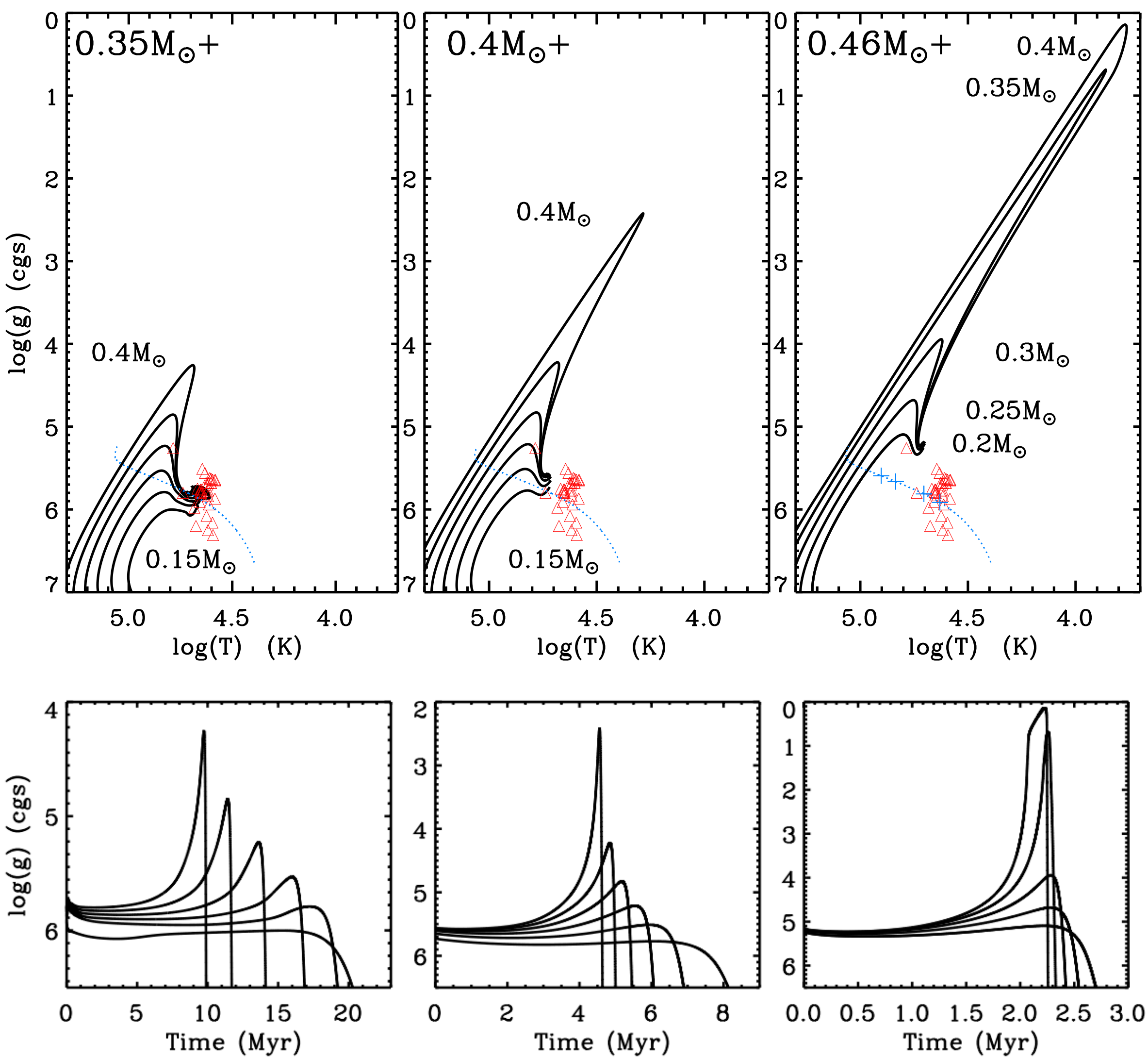

Figure 2. The post-merger evolutionary tracks of stars formed by mergers of post-sdB WDs with helium WDs. The panels show the tracks for mergers of a 0.35 $M_\odot$ (left), 0.4 $M_\odot$ (centre) and 0.46 $M_\odot$ (right) post-sdB star, respectively, with a range of different helium masses (in steps of 0.05 $M_\odot$, as labelled). The red triangles show the locations of the He-sdOs given in Stroeer et al. (2007). The dotted curve in each upper panel indicates our theoretical helium main sequence; in the right hand panel we mark helium main sequence masses of 3, 2, 1 and 0.7 $M_\odot$ (left–right) with plus symbols. The lower row of panels shows the time evolution of the surface gravity of these stars. Note that they spend the majority of their lifetimes near to the start of the tracks, close to the observed He-sdO stars, especially for the stars formed from the 0.35 $M_\odot$ post-sdB stars.

for our models to converge; we typically added mass at a rate that was over an order of magnitude smaller than the Eddington-limited accretion rate. Although the initial thermal structure of these objects will not be a perfect match to that of the actual merger products, it will adjust itself on a thermal timescale. Hence we do not expect the subsequent nuclear evolution of the stars to be significantly affected.

Our 0.35 $M_\odot$ sdB stars are so cold and degenerate by the time that they have completely exhausted their core He that we could not follow mergers when starting from those structures. For these 0.35 $M_\odot$ objects, we were able to take less degenerate models ($\psi_{\rm core} \approx 4$, where ψ is the degeneracy parameter [see, e.g., Kippenhahn & Weigert 1990]) with almost no core helium ($\log Y_{\rm core} < -8$) and set the core helium fraction to zero by hand. We could then add matter to the surface of these objects and follow the helium burning and subsequent evolution. When we tried to perform mergers using stellar structures where the core helium had not been reduced to zero, convection currents were driven by the residual core helium burning, leading to significant mixing throughout the star.

We investigated whether the age of the post sdB WD affected its post-merger evolution, i.e. whether the core temperature and degeneracy parameter ψ at the time of the merger were significant. This is not easy to study faithfully as our calculations often fail to converge when the point of helium ignition has become even mildly degenerate ($\psi \gtrsim 2$). However, we adopted an artifical way to test this. For a merger product which was not degenerate enough to cause numerical problems, we switched off the nuclear evo-

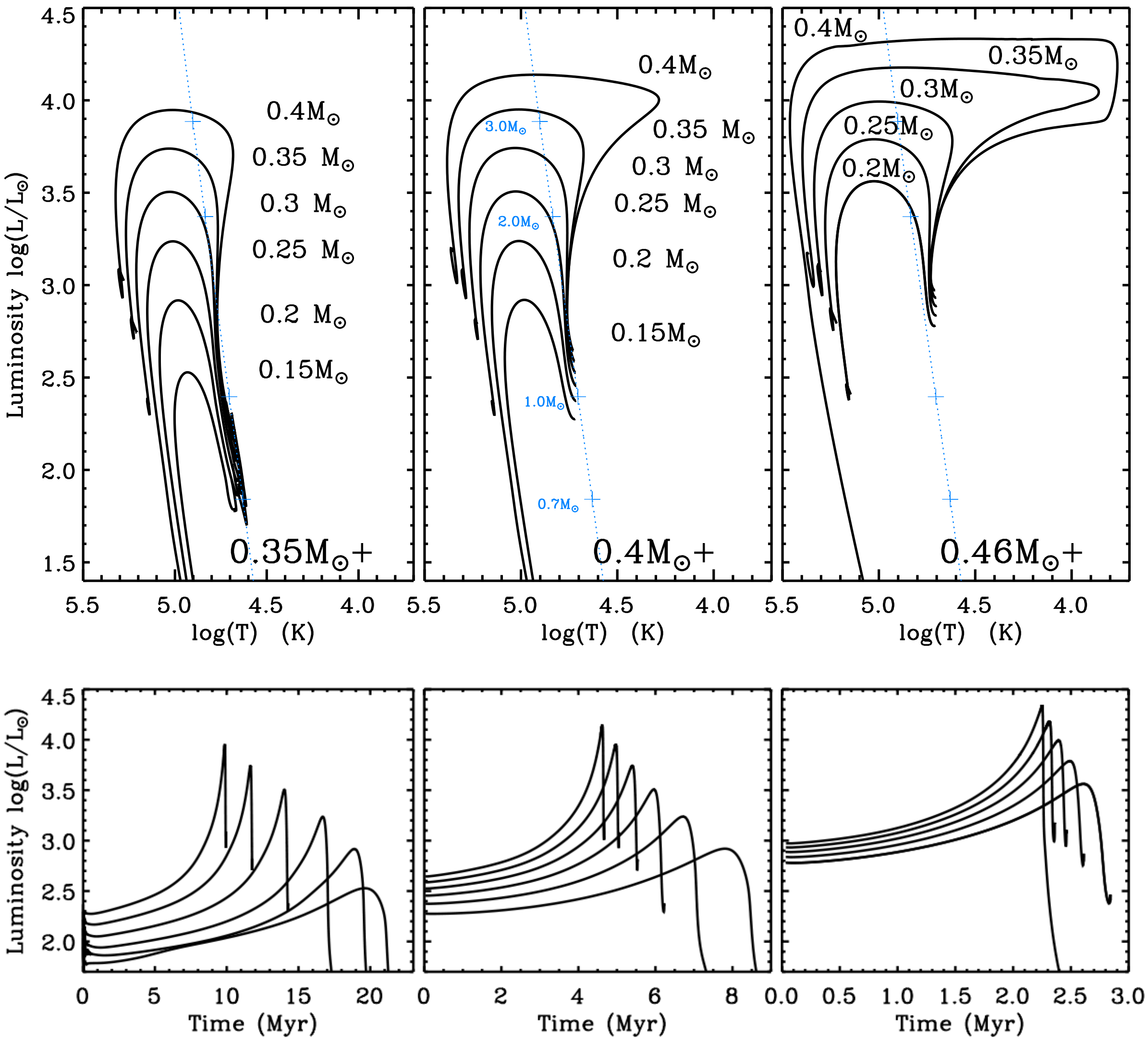

Figure 3. The same stellar calculations as in Fig. 2, but this time showing the luminosity evolution of the stars. The overall evolution in the HR diagrams is from right to left. These merger products are significantly more luminous than canonical sdB stars. The dotted curve in each upper panel shows our theoretical helium main sequence; helium main sequence masses of 3, 2, 1 and 0.7 $M_\odot$ are marked with plus symbols.

lution whilst allowing the helium-burning energy generation to continue. We then forcibly cooled the core as much as possible. For lower helium WD masses (e.g. 0.2 and 0.25 $M_\odot$), we were able to reach core temperatures as low as 10^6 K, and in all cases below 10^7 K. The initial core temperature appeared to have no discernible effect on the long-term evolution of the merger product once the artificial cooling was removed; the core temperature increased again due to heat flowing inwards from the burning shell. We also note that compressional heating of the accreting star during the merger should reduce the degeneracy of the merger products compared to our hydrostatic calculations, potentially further reducing any small effect of the core temperature at the time of the merger. However, we cannot guarantee that this effect can be totally ignored; similar calculations have been performed by Iben (1990), who argued that the prior thermal history of the core was not negligible in the evolution of the post-merger star.

The results of our calculations are shown in Figs. 2 and 3. The majority of the helium-burning phase of the merger products is spent close to the majority of known He-sdO stars in the effective temperature – surface gravity diagram. This is particularly true for mergers of the 0.35 $M_\odot$ post-sdB stars. Furthermore, the trend from the 0.4 to 0.35 $M_\odot$ models suggests that the lowest mass sdB stars in the population (≈ 0.3 $M_\odot$; see Fig. 1) might help to fill in the low-temperature end of the distribution. Pronounced helium-giant phases are experienced late in the evolution of the merger products when the total mass exceeds ≈ 0.8 $M_\odot$,

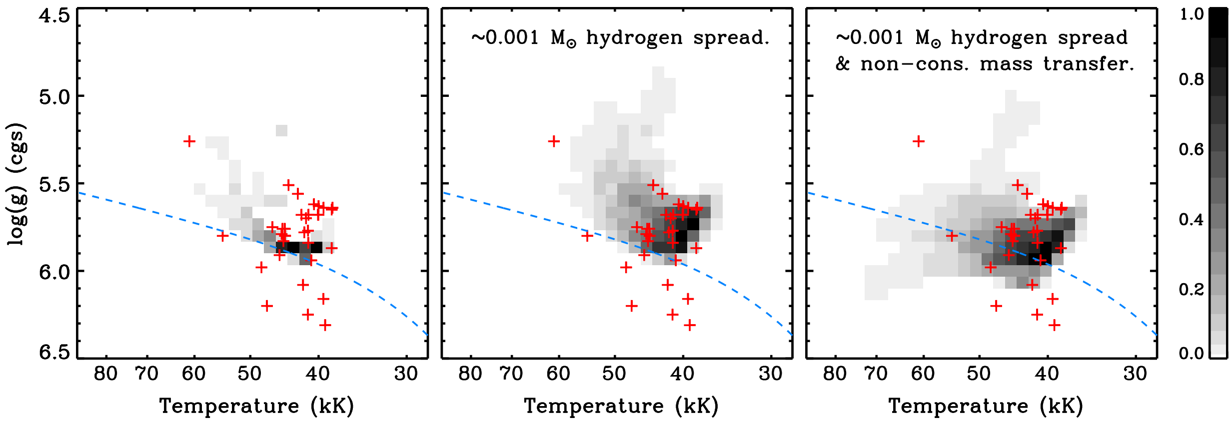

Figure 4. Population synthesis results for single He-rich sdOs, showing the distributions of surface gravity g and effective temperature; darker regions indicate a higher density of systems. The crosses represent the observed He-rich sdO stars listed by Stroeer et al. (2007). The broken curve in each panel shows our theoretical helium main sequence. The left panel shows the outcome for our hydrogen-free grid of stellar tracks, weighted by the results for close binary sdBs of Han et al.'s (2003), assuming that the binary components merge completely. In the central panel, the appearance of that same population is modified to take into account trace amounts of hydrogen remaining in the stellar atmospheres ($\lesssim 0.001\mathrm{M}_\odot$; see text for details). The right panel is similar to the central panel, but also assumes that the merger process is non-conservative and that 0.1 $\mathrm{M}_\odot$ of the helium WD is not accreted. Only the small fraction of stars with the highest surface gravities seem difficult to explain, but those stars seem likely to have their surface gravitites adjusted as atmospheric models improve (see, e.g., Hirsch & Heber [2009]).

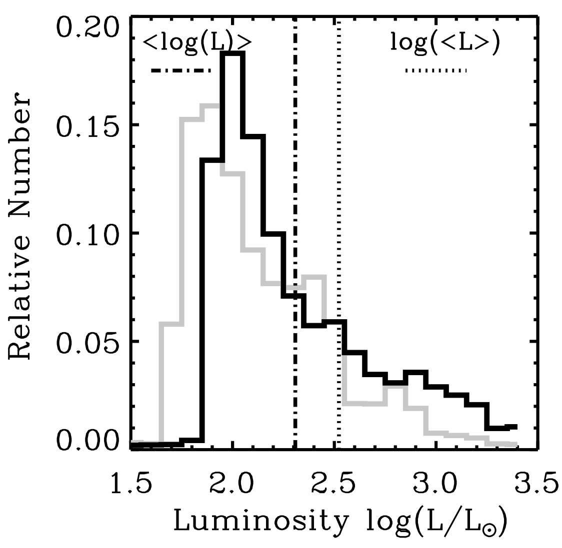

Figure 5. The black histogram shows the luminosity distribution taken from the population synthesis simulation which assumes that all of the He WD is accreted onto the newly-formed He-sdO star. Both the mean luminosities marked by vertical lines refer to that model. The light grey curve shows the distribution if we assume that 0.1 $\mathrm{M}_\odot$ of the He WD is somehow not accreted. In this case, the mean luminosity drops from ≈ 300 $\mathrm{L}_\odot$ to ≈ 200 $\mathrm{L}_\odot$.

in agreement with the behaviour described by Trimble & Paczynski (1974) for low-mass He stars.[5]

[5] Note that these helium giants may experience a large amount of wind mass loss not included in our calculations.

2.2 Population synthesis

We have generated a library of evolutionary sequences for post-sdB + He WD merger products, as described in the previous section. We then combined that library with the sdB population predictions by Han et al. (2003) to simulate the characteristic properties of the expected population of single He-rich sdO stars from this merger channel. Figure 4 compares the results of such a population synthesis simulation to the properties of observed He-rich sdO stars from Stroeer et al. (2007). We show the results for two assumptions: one where all of the He WD is accreted by the post-sdB star and one where 0.1 $\mathrm{M}_\odot$ of the He WD is lost from the system, to take into account possible systemic mass loss or the formation of a disc around the merger product; a real population is likely to have a more complicated combination of conservative and non-conservative mass-transfer histories. The correspondence between our models and the observations is quite good, especially when we apply a correction to mimic the effects of small amounts of hydrogen in the atmospheres of the sdO stars.

Our initial sdB models were completely hydrogen-free. However, even a thin hydrogen envelope layer significantly changes the appearance of a hot subdwarf (Han et al. 2002), making it cooler and reducing its surface gravity. To take this into account, Fig. 4 shows the population synthesis results both with and without an ad-hoc correction for trace amounts of hydrogen, as estimated from figure 2 of Han et al. (2002). We chose to uniformly spread each system in the T_{eff}–$\log g$ plane over a range given by the vector -5000 K in T_{eff} and 0.3 in $\log g$.[6]

We note that Stroeer et al. (2007) find that He-rich

[6] This is consistent with figure 2 of Han et al. (2002) for a H-rich envelope mass of 0.001 $\mathrm{M}_\odot$, i.e. we assumed a uniform spread in H content from zero to $\approx 0.001\mathrm{M}_\odot$. In reality, both the magnitude

sdO stars show higher carbon and nitrogen abundances than other sdO stars. This seems consistent with our proposed formation channel, as mixing during the merger phase could mix out material from the core of the post-sdB star. However, the effect of these surface abundance changes has not completely been taken into account in our stellar evolution calculations. These abundances may also affect the atmospheric modelling of these stars (e.g. Lanz et al. 2004 & Stephan Geier, priv. comm.), hence some of the parameters of the observed He-sdO stars may change as the atmospheric models improve.[7] It seems likely that our model could, in principle, account for most of the He-sdOs above the helium main sequence. However, several He-sdOs below the He main sequence can apparently only be accommodated by our simulations if their surface gravities decreased as a result of improved atmosphere calculations; the work of Hirsch & Heber (2009) suggests that such an adjustment is very likely to occur.

2.3 Population estimates

We now estimate the birthrate of single He-rich sdOs, using the binary population synthesis calculations of Han et al. (2003). The formation channel which produces sdB stars in close binaries with helium WDs is their 'second common-envelope channel' (CE2). Their two common-envelope channels produce the sdB stars known to be in close binaries, which constitute about half of the known systems (we will denote the fraction of sdB stars which are in close binaries as $f_{\rm bin}$). For their model population which best fits the Galaxy, the CE2 birthrate is $2.98 \times 10^{-3}\,{\rm yr}^{-1}$ and the CE1 birthrate is $8.62 \times 10^{-3}\,{\rm yr}^{-1}$, i.e. $\approx 26\%$ of the close binary sdBs come from the CE2 channel. However, for the common-envelope parameters used in their preferred model, only $\approx 10\%$ of the binaries produced via the CE2 channel are close enough to merge within 10 Gyr.[8] Hence we estimate the birthrate in the Galaxy of He-rich sdOs ($B_{\rm He-sdO}$) to be $\sim 3\%$ of the birthrate of close binary sdBs ($f_{\rm bin} B_{\rm sdB}$).

Given the birthrates, we can estimate the relative number of sdB and He-sdO stars using their respective lifetimes. For the He-sdO population, we find a mean lifetime ($\tau_{\rm He-sdO}$) of ≈ 10 Myr and, for sdB stars, we adopt the canonical lifetime $\tau_{\rm sdB} \approx 100$ Myr. The number of stars in the He-rich sdO population, $N_{\rm He-sdO}$, is then related to the number of sdB stars, $N_{\rm sdB}$, according to

$$N_{\rm He-sdO} = f_{\rm bin} N_{\rm sdB} \frac{\tau_{\rm He-sdO}}{\tau_{\rm sdB}} \frac{B_{\rm He-sdO}}{f_{\rm bin} B_{\rm sdB}}, \qquad (1)$$

i.e., using the estimates above,

$$N_{\rm He-sdO} \sim 0.5 \times N_{\rm sdB} \times 0.1 \times 0.03 \approx \frac{N_{\rm sdB}}{667}. \qquad (2)$$

Thus, there should be ~ 700 times as many sdB stars as He-rich sdO stars in the *intrinsic* population. However, since He-rich sdOs are on average much brighter, this need to be corrected for the different potential detection volumes in order to be able to derive an estimate for the relative number in the *observed* sample. Figure 2.1 shows the luminosity distribution of the predicted He-sdO population. While a representative luminosity for a sdB star is ~ 15 L$_\odot$ (Han et al. 2003), the mean luminosity of the He-sdO population is $\sim 300\ L_\odot$ (see figure 2.1). This gives a relative detection volume of $\sim 20^{1.5} \approx 90$.[9] This estimate implies that there should be one He-sdO star known for every $\sim 700/90 \approx 8$ sdB stars.

This is clearly a very approximate number. It assumes that we know both the number of systems produced by the CE2 formation channel and the fraction of those systems which have short enough periods to merge within a Hubble time. Uncertainties in the CE2 channel include the treatment of common-envelope evolution itself, the extent to which the first mass transfer phase is non-conservative and the criterion for dynamically unstable mass transfer.

However, our estimate for the relative numbers of He-rich sdOs and sdB stars seems to be a reasonable match to the observations. We are not aware of samples that can be compared precisely, but Stroeer et al. (2007) list 33 He-rich sdO stars; in a companion paper, Lisker et al. (2005) state that over 200 sdB stars have been 'analysed for atmospheric parameters'. Heber (2008) increases that number to 'several hundred' sdB stars. The Palomar-Green survey (Green, Schmidt & Liebert 1986) found ~ 1 He-sdO for every 4 sdBs.[10]

2.4 A comparison with He-WD mergers

There seems to be little doubt that He-WD+He-WD mergers (Saio & Jeffery 2000) and He-WD+post-sdB mergers (this work) both happen. The potential difference between the outcomes of those events is worth examining. Han et al. (2002, 2003) and Han (2008) have argued that double He-WD mergers can explain single *H-rich* sdB stars, whilst here we argue that He-WD+post-sdB mergers can produce *H-poor* He-sdO stars.

The difference between the atmospheres of sdB and sdO stars should be able to account for this. Groth, Kudritzki & Heber (1985) examined the occurence of convection zones in hot subdwarf stars as a function of temperature and composition; they argued that the atmospheres of helium-rich sdO stars should be convective, whilst those of helium-poor sdOs

and direction of this vector should change slightly with effective temperature.

[7] For example, Lanz et al. (2004) state that composition effects can produce a systematic error of 0.5 dex in the derived surface gravity of PG 1544+488.

[8] This requires a post-common-envelope period $P_0 \lesssim 7$ hr, assuming that gravitational wave radiation is the only angular-momentum loss mechanism and taking representative component masses of 0.35 & 0.45 M$_\odot$.

[9] This assumes a homogeneous spherical distribution of objects, which is unlikely to be an ideal approximation for stars of this luminosity within the Galactic disc. In the other extreme limit of a cylindrical thin-disc population, the ratio of detection volumes would be 20.

[10] In the SPY sample of hot subdwarfs (Napiwotzki et al. 2004; Lisker et al. 2005; Stroeer et al. 2007), sdO stars are likely to be over-represented with respect to sdB stars due to the selection criteria for the target list (Stroeer et al. 2007); thus using the ratio of 33 He-sdOs to 76 sdBs published by that survey would be misleading. We do not know to what extent other selection effects affect the relative numbers in the published sdB and He-sdO populations.

and sdB stars are mostly radiative (see also Heber [2009]). Hence gravitational settling can operate in most sdB stars – producing He-poor photospheres – but not in He-sdOs. The effective temperatures of the merger products thereby determine which remain He-rich; the cooler merger products experience settling. The majority of He-WD mergers simulated in Han et al. (2002) are significantly cooler than the merger products in Fig. 4, consistent with the He-WD mergers producing H-rich sdBs and the merger channel proposed in this work producing He-sdOs.

However, if that explanation is correct then the hotter He-WD mergers may also contribute to the He-sdO population. In addition, note that the boundary between the atmospheric regimes found by Groth et al. is more complex than simply a division between sdO and sdB stars; in particular, their calculations found that the temperature boundary which allows a convective atmosphere becomes cooler at lower surface gravities.[11] Hence we should also expect some He-sdB stars to be produced by He-rich merger products which have convective atmospheres but are cool enough to be sdB stars.[12] This would be helpful to our model, since it seems that our merger products are too hot to explain He-sdB stars. Naslim et al. (2010) have stressed that it is logical to consider the evolutionary status of He-sdB and He-sdO stars together; our merger scenario seems to require a second population to explain the He-sdBs: potentially some He-WD mergers account for the He-sdBs as well as for the some of the He-sdOs.

One outstanding and, as yet, unexplained piece of evidence is the observation that He-sdOs come in both nitrogen-rich and carbon-rich classes, with a further subset enhanced in both C and N, whilst He-poor sdOs are not C or N rich (Stroeer et al. 2007). If some He-WD mergers produce He-sdOs (perhaps, e.g., the more massive He-WD mergers) then they might conceivably produce one composition subclass whilst the He-WD+post-sdB mergers produce another subclass. Saio & Jeffery (2000) argue that the outcome of their double He-WD merger model could have CNO-processed material at the surface (i.e. N-rich), whilst Saio & Jeffery (2002) produce a C-rich star from their He-WD+CO-WD merger (*not* a He-sdO).[13] Our merger model is somewhere between those examples; it is not clear which range of surface abundances our merger scenario might produce. The phase of accretion and ignition seems likely to be important for imprinting the surface carbon and nitrogen abundances of He-sdOs; we encourage future work to investigate this detail.

3 THE DOUBLE HE-RICH SUBDWARF STARS

The model described by this paper so far can explain the population of observed single He-rich sdO stars quite well.

[11] Compare, e.g., figure 7 of Groth et al. with the continuous extension of the He-sdO population into the He-sdB stars in, e.g., figures 4 and 5 of Naslim et al. (2010).

[12] Perhaps some He-rich subdwarfs could also be observed whilst their atmospheres are still experiencing gravitational settling.

[13] He-sdBs are generally N-rich, consistent with being He-WD mergers, but the few C-rich examples are more puzzling (see, e.g., Naslim et al. 2010).

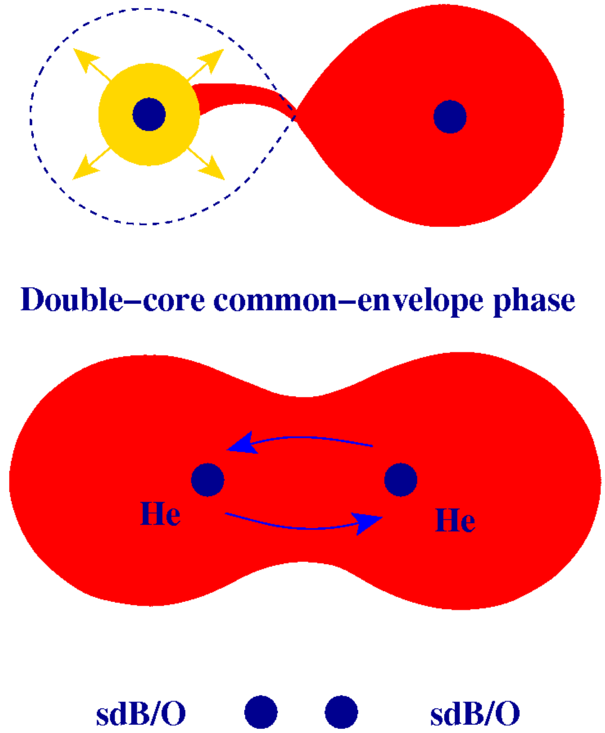

Figure 6. The double-core common-envelope channel. In a binary with binary components of comparable mass, the primary fills its Roche lobe after the secondary has completed its main-sequence phase and has developed a helium core. This leads to a common-envelope phase, where the helium cores of the two stars spiral inside a common-envelope formed from their joint envelopes. After the ejection of the common envelope, the system may appear as a binary consisting of two hot subdwarfs.

However, there are two known *double* He-rich hot subdwarf stars, i.e. binaries where both components are He-sdO or He-sdB stars. Interestingly, both of these systems contain two hot subdwarfs that appear to be He-rich.

The best published example of such a system is PG 1544+488 (Ahmad et al. 2004), which contains two He-rich hot subdwarf stars. The published mass ratio for that system is 1.7 ± 0.2, though recent data may bring this value closer to 1 (Simon Jeffery, priv. comm.). The orbital period is 0.48 d. Lisker et al. (2004) also report the existence of a system containing two 'very similar' He-rich sdO stars (HE 0301-3039; see also Stroeer et al 2007).

A second formation channel is needed to explain these systems: we suggest that these systems are the products of a double-core common-envelope (CE) phase (e.g. Brown 1995; Belczynski & Kalogera 2001; Dewi, Podsiadlowski & Sena 2006). Double-core CE evolution is a special case of common-envelope evolution where the envelopes of *both* stars in a binary are simultaneously ejected as both stellar cores spiral inwards inside an envelope produced by the union of their envelopes. This produces a close binary containing the exposed cores of both original stars (see Fig. 6).

The onset of double-core evolution, should it occur, is not driven by the classical dynamical mass-tranfer instability, since the initial mass ratio of the two binary components has to be close to one, which generally leads to dynamically stable mass transfer. However, mass transfer onto the sec-

ondary, which is already trying to expand as a [sub-]giant, causes it to swell further. Both stars are then trying to overfill their Roche lobes, leading to the spiral-in and ultimately the ejection of the shared envelope. Double-core evolution has not been proven to exist in nature. However, if it is responsible for the production of double hot subdwarf binaries, then this may have potentially important implications for the production of double neutron-star binaries through an analogous channel (e.g. Dewi et al. 2006).

The parameter space which is expected to lead to double-core CE evolution is quite small. The two stars in the binary must have almost equal initial masses, as the secondary must have already left the main sequence by the time the primary fills its Roche lobe whilst the primary should fill its Roche lobe before the tip of the first giant branch. In order to form two hot subdwarfs, there is a further constraint: both stars must be able to ignite helium. The consequence of this constraint depends on the initial mass of the stars; there are two regimes which divide approximately into whether the secondary ignites helium degenerately or non-degenerately.

If the secondary is to ignite helium degenerately, its core mass must be within $\sim$ 5% of the core mass at the tip of the giant branch when the envelope is removed (Han et al. 2002). This requirement also applies at the lower end of the mass range when non-degenerate ignition is possible. The likelihood of both components being within this range at contact is almost negligible, as can be seen from Fig. 7, which quantifies the parameter constraints for this channel.

If we neglect the unlikely possibility that the secondary ignites helium degenerately, both components will be igniting helium non-degenerately. According to Han et al. (2002), stars more massive than 2.265 $M_\odot$ will, at solar metallicity, ignite helium non-degenerately even if they lose their envelopes in the Hertzsprung gap.[14] This allows a wider range of parameter space to potentially produce double-hot-subdwarf systems. Figure 7 shows the width of the non-degenerate double-core channel. At the lower end of this mass range, the mass of the secondary has to be within $\approx$ 0.5 % of the mass of the primary, declining to $\approx$ 0.3 %. This is narrow but not completely negligible. If we make the standard assumption that the probability distribution of mass ratios is $p(M_2/M_1) \propto M_2/M_1$ (where $M_2/M_1 \leqslant 1$), then, for non-degenerate ignition, around 1 % of systems in the first common-envelope channel from Han et al. (2002, 2003) meet this criterion. However in the preferred population model of Han et al. (2003), only $\approx$7% of the close sdB binaries are produced via non-degenerate ignition in the first CE channel.[15] Assuming that half of the known sdBs are in close binaries, then only one double-core system is born for every $\sim$3000 normal sdBs. If that estimate is correct, then the birthrate from this channel seems somewhat lower than would comfortably account for seeing two such systems amongst several hundred known sdB stars. However, the two known systems consitute a very small sample size, and we do not attempt to account for observational selection effects.

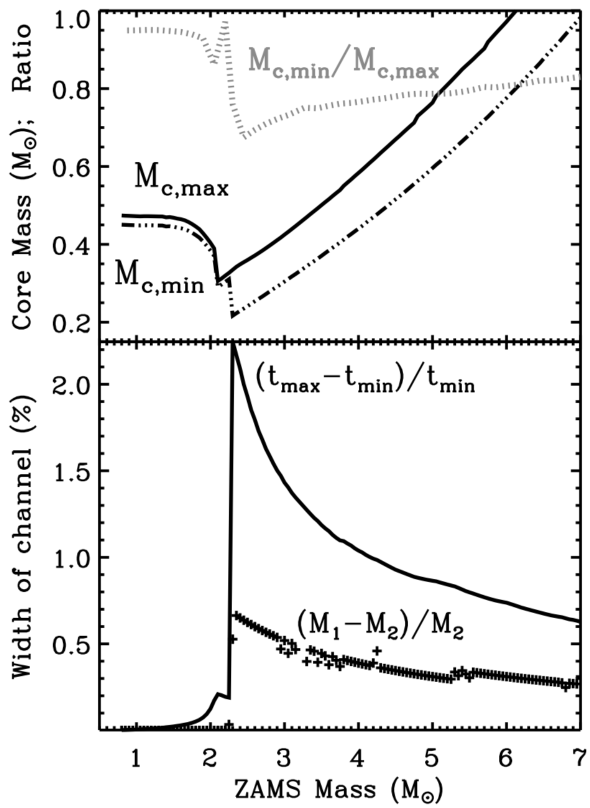

Figure 7. Parameter constraints for the double-core channel. The upper panel shows the maximum and minimum core masses (respectively the solid and broken black curve) that could ignite helium after the removal of the stellar envelope in the double-core channel (as a function of zero-age main sequence [ZAMS] mass, $M_{\rm ZAMS}$; see also Han et al. 2002). The broken grey curve shows the ratio of those core masses, i.e. it gives an estimate for the most extreme hot subdwarf mass ratios which could be produced by the double-core channel. The lower panel illustrates how the various constraints relate to time and mass-ratio constraints. The solid curve shows the fractional lifetime difference between $t_{\rm min}$ and $t_{\rm max}$, the minimum and maximum age for a given $M_{\rm ZAMS}$ when the primary is able to enter into a double-core CE phase. We do not calculate the energetics of the common-envelope ejection phase. The crosses indicate how this lifetime constraint translates into a fractional mass difference constraint for the two stars if they are *both* to be able to become helium-burning hot subdwarfs simultaneously in this channel. The scatter in the crosses is numerical noise. At best, the initial masses of the stars must be within $\approx$ 0.5%. Instances of double-core evolution after which both stars can *degenerately* ignite helium are highly improbable.

Figure 7 also shows that hot subdwarf systems produced from this channel should have mass ratios $1.0 \leqslant M_1/M_2 \lessapprox 1.3$, based on the ratio of allowed core masses.[16]

A third possibility is that the core of the secondary star does not ignite helium at all. Then the observed system would not contain two He-burning stars, but one He-burning

[14] At z=0.004, this threshold drops to 2.0 $M_\odot$; hence adopting a lower metallicity seems likely to increase the birthrate from this channel.

[15] Only 12% of the sdBs from their first common-envelope channel experience non-degenerate ignition.

[16] Note that the definition of the core mass here is based on composition (i.e., $\sim$complete H-exhaustion), which is somewhat approximate for intermediate-mass stars at the end of the main sequence.

star and one post-RGB star that is simply a hot young WD, cooling towards the main WD cooling sequence (HD 188112 seems to be an example of such a non-He-burning hot subdwarf; see, e.g., Heber et al. 2003; Stroeer et al. 2007). The lifetime of this cooling phase is short ($\sim 1 - 10$ Myr, depending on its mass; Driebe et al. 1998; Heber et al. 2003). It seems unlikely to us that the non-He-burning secondary would resemble the primary for long enough to reproduce the systems we are considering here, but this possibility cannot be totally excluded.

3.1 A non-double-core channel for dual hot subdwarfs

The double-core CE evolution channel outlined above is not the only possible way to make a binary containing two hot subdwarfs. Rappaport et al. (2009) have outlined the evolutionary past and future of the spectroscopic binary Regulus (α Leonis). The current low-mass (~ 0.3 M$_\odot$) component could potentially be a very low-mass sdB star. In one of the possible paths for the future evolution of the system, the core of Regulus (the current main-sequence star with mass ~ 3.4 M$_\odot$) is exposed as a second sdB star, of mass $\sim$ 0.5 M$_\odot$. In such a scenario, the lower-mass sdB star could easily be still burning helium after the second one has been formed. If the current low-mass star did not manage to ignite helium, then a system with only marginally different initial conditions should be able to do so. The Regulus-like systems would produce a hot subdwarf binary with a mass ratio far from unity ($\sim 0.5/0.3 \approx 1.7$), similar to the published mass ratio of PG 1544+488.

There may well be even more channels which can produce double hot subdwarfs as binary evolution allows for a rich range of possibilities. However, the double-core channel tends to produce systems with mass ratios approaching one with minimal appeal to fine-tuning. In addition, one distinguishing feature of both PG 1544+488 and HE 0301-3039 is that they seem to be He-rich. For a Regulus-like channel it is not so obvious why this should produce abnormal sdB stars, as they are simply a combination of normal formation channels. Hence it seems reasonable to ask whether double-core evolution might somehow tend to produce He-rich subdwarfs.

3.2 Helium rich subdwarfs from double-core evolution?

As explained above, the double-core channel strongly favours non-degenerate helium ignition and hence intermediate-mass stars (see Fig. 7). Figure 8 shows that, during the relevant portion of their evolution, intermediate-mass stars can have extended regions outside their cores which have high helium abundances, whilst low-mass stars do not. This seems to provide a natural reason why the known double subdwarf stars are He-rich.[17]

If intermediate-mass stars tend to produce He-rich hot subdwarfs, then the mass distribution of that subdwarf population should be less strongly peaked than the general sdB population. This is because those sudwarfs from intermediate-mass stars can ignite helium non-degenerately, unlike those low-mass stars which experience the helium flash.

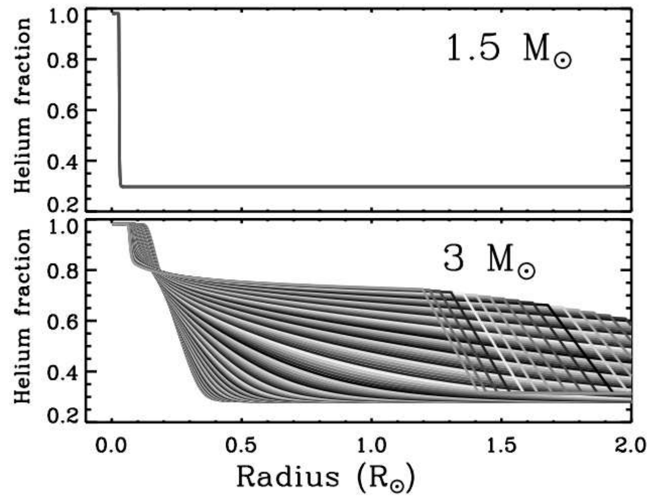

Figure 8. Comparison of the helium composition profiles of low- and intermediate-mass stars (1.5 and 3 M$_\odot$, respectively) during the evolutionary stage(s) in which they could lose their envelopes and still ignite helium in their cores. Many different profiles are shown for the 3 M$_\odot$ star, so a greyscale is used to separate adjacent curves. The displayed radius range displayed highlights the region near the core which is likely to become exposed after the ejection of the envelope during double-core evolution. The 1.5 M$_\odot$ star has a sharp transition between its He-rich core and hydrogen-rich envelope. In contrast, the structure of the 3 M$_\odot$ star allows a relatively high helium abundance outside the core during the period when double-core evolution might operate.

4 SUMMARY AND CONCLUSIONS

We have calculated the evolution of post-sdB WD stars after they have accreted from (or merged with) a helium WD companion. These stars burn helium in a shell around the core, but spend a large part of their evolution with properties mainly determined by the sdB mass. Their later radius evolution is mainly determined by the mass of helium gained from their WD companions. The only major uncertainty in our modelling is in the treatment of the merger phase and the degenerate He ignition, but the merger calculations of Saio & Jeffery (2000, 2002) seem to support our assumptions.

This demonstrates that one of the major binary channels for the formation of sdB stars considered by Han et al. (2002, 2003) *predicts* objects which resemble He-rich sdO stars. This subset of sdO stars 'cannot be explained with canonical single star evolutionary models' (Stroeer et al. 2007). An extension of this model could include mergers of He WDs with other low-mass CO WDs; however, massive sdB stars which leave remnants resembling normal-mass CO WDs probably do not produce He-sdOs (see Saio & Jeffery 2002). He-sdOs produced by this scenario have relatively high luminositites compared to sdB stars, which may help

[17] An alternative possibility, which we cannot rule out at this stage, is that the process of envelope ejection during the double-core CE phase is somehow systematically different to that of standard common-envelope evolution.

to distinguish between this and alternative scenarios (e.g. Saio & Jeffery 2000; Miller Bertolami et al. 2008).

More speculatively, we have also argued that systems containing two hot subdwarfs (e.g., PG 1544+488, Ahmad et al. 2004; HE 0301-3039, Lisker et al. 2004) could form through double-core common-envelope evolution. This generally requires that the subdwarfs have similar masses and favours intermediate-mass progenitors. Since intermediate-mass giants have a rather different chemical profile, this may also naturally explain why hot subdwarfs in these systems are preferentially He-rich.

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